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Contents

Abstract

An inconsistency arises in Rothermel's fire spread model when there are two or more categories. If a fuel load is split into identical classes in two separate categories, the reaction intensity is less than if the load is contained in a single class in one category. The author resolves the inconsistency by replacing the weighting parameter for each category with the effective heating number developed from the characteristic surface area-to-volume ratio of each category.

OXFORD: 431.5:431.6. KEYWORDS: ignitibility, fire behavior, fire spread model, effective heating number, weighting parameter.

Introduction

The formulations found in Rothermel's fire model[1] were derived from observations of fire spread through homogeneous fuel arrays. In order to correlate these data to heterogeneous fuel arrays, which are more often encountered in the field, Rothermel developed a method of "homogenizing" the fuel sizes into one characteristic size for each fuel type or category. The reaction intensity contribution from each category was then calculated and summed to give the total reaction intensity leading to the final calculation of the rate of spread.

The homogenizing process for combining either classes or categories was achieved by weighting each size class by its surface area. Thus, for equal loads, smaller diameter fuels are given greater weight to obtain the characteristic fuel size for that category.

My purpose is to show that if more than one category is used and identical fuels are entered or generated in each category, the weighting method will produce an inconsistency. The total reaction intensity and the resultant rate of spread will be less than if all the fuel were contained in one category. However, it follows that if a single category is used (e.g., dead fuel), no problems arise.

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[1]Richard C. Rothermel. A mathematical model for predicting fire spread in wildland fuels. USDA For. Serv. Res. Pap. INT-115, 40 p., illus. 1972.

Fire Spread Model Inconsistency

The problem is illustrated by using Rothermel's fire spread model to compute the rate of spread from the following list of fuel data:

Dry load--(0.034 lb./ft.^{2})
Low heat value--(8,000 B.t.u./lb.)
Fractional moisture content---------------------------------(0.04 lb./lb.)
Fractional extinction moisture content----------------------(0.30 lb./lb.)
Surface area-to-volume ratio--------------------------------(3,500 ft.$^{-1}$)
Fractional mineral content----------------------------------(0.06 lb./lb.)
Particle density--(32 lb./ft.^{3})
Effective fractional mineral content------------------------(0.01 lb./lb.)
Fuel depth--(1 ft.)
Wind--(0 ft./min.)
Slope---(0 ft./ft.)

Two examples are given for comparison. First, the fuel load is entered into a *single* category, then *split* equally into two categories. The differing results are shown in table 1.

Table 1.--*Two computations of the rate of spread.*

Option	Reaction intensity			Rate of spread
	Category 1	Category 2	Total	
	B.t.u./ft.^{2}-min.			Ft./min.
Single *	1,070	--	1,070	6.4
Split †	267	267	534	3.2

*Load contained in one category.
†Load split equally into two categories.

The following illustrates this inconsistency algebraically. For a given size class, entering the load into one category gives twice the intensity of the same load equally divided into two categories. The differences occur in the weighting parameters in the reaction intensity equation (58).[1]

$$I_R = \Gamma' \sum_{i=1}^{i=m} f_i (\tilde{w}_n)_i (\tilde{h})_i (\tilde{\eta}_s)_i (\tilde{\eta}_m)_i ,$$

where,

$\tilde{w}_n$ = net load

$\tilde{h}$ = low heat value

$\tilde{\eta}_s$ = mineral damping coefficient

$\tilde{\eta}_m$ = moisture damping coefficient

$(\ )_i$ = in i^{th} category.

In the split load, the heat content, mineral damping, and moisture damping coefficients of each category are equivalent to their corresponding parameters in the single category. The weighting parameters of the split load are equal and each has a value of ½ because their sum must be 1. For one class in a single category there is one weighting factor, $f_i = 1$, and the reaction intensity is:

$$I_{Ra} = \Gamma' (\tilde{w}_n)_1 \tilde{h}_1 (\tilde{\eta}_s)_1 (\tilde{\eta}_m)_1 .$$

When the load is split equally into one class in each of two categories, the weighting parameters are:

$$f_1 = f_2 = \tfrac{1}{2},$$

so that,

$$I_{Rb} = \Gamma' [\tfrac{1}{2}(w_n/2)_1 \tilde{h}_1 (\tilde{\eta}_s)_1 (\tilde{\eta}_m)_1 + \tfrac{1}{2}(w_n/2)_2 \tilde{h}_2 (\tilde{\eta}_s)_2 (\tilde{\eta}_m)_2].$$

But,

$$(w_n/2)_1 \tilde{h}_1 (\tilde{\eta}_s)_1 (\tilde{\eta}_m)_1 = (w_n/2)_2 \tilde{h}_2 (\tilde{\eta}_s)_2 (\tilde{\eta}_m)_2 .$$

Therefore,

$$I_{Rb} = \Gamma' (w_n/2)_1 \tilde{h}_1 (\tilde{\eta}_s)_1 (\tilde{\eta}_m)_1$$

$$I_{Rb} = \tfrac{1}{2}\, \Gamma' (w_n)_1 \tilde{h}_1 (\tilde{\eta}_s)_1 (\tilde{\eta}_m)_1 ,$$

which gives:

$$I_{Rb} = \tfrac{1}{2} I_{Ra}.$$

But, since the load and fuel characteristics are equivalent, we should have:

$$I_{Rb} = I_{Ra}.$$

This argument can be expanded to n categories where the fraction of inequality is 1/n.

The above example is the worst case. The fraction I_{Rb}/I_{Ra} approaches 1 (completely consistent) as the fraction of the load in one category decreases from ½ to zero or increases from ½ to 1.

The Solution

To resolve this inconsistency the weighting parameter, f_i, was replaced by the effective heating number, evaluated from the characteristic surface area-to-volume ratio of each category. Explicitly, f_i in equation (58)[1] was replaced by

$$\varepsilon_i = \exp(-138/\tilde{\sigma}_i),$$

where $\tilde{\sigma}$ is the characteristic surface area-to-volume ratio of the i^{th} fuel category. Results using ε_i are given in table 2.

The general effect of exchanging the weighting parameter for the effective heating number is for the calculated rate of spread to increase if the fuel is distributed into more than one category (presently two, live and dead) and to decrease by a lesser

Table 2.--*Computations of the rate of spread modified by weighting the reaction intensity calculation by the effective heating number.*

Option	Reaction intensity			Rate of spread
	Category 1	Category 2	Total	
	-------------	B.t.u./ft.^{2}-min.	-------------	Ft./min.
Single*	1,028	--	1,028	6.2
Split †	514	514	1,028	6.2

*Load contained in one category
†Load split equally into two categories.

amount if the fuel is limited to one category. Figure 1 shows how three fuel models:[1] chaparral, timber (litter and understory), and slash (heavy, 200 T/A) are affected by exchanging the weighting parameter. The first two models, chaparral and timber, show increases when the effective heating number is used, whereas the slash model shows a decrease. Results are consistent with the fact that both fuel models, chaparral and timber, have two categories, live and dead, and slash has only one, dead.

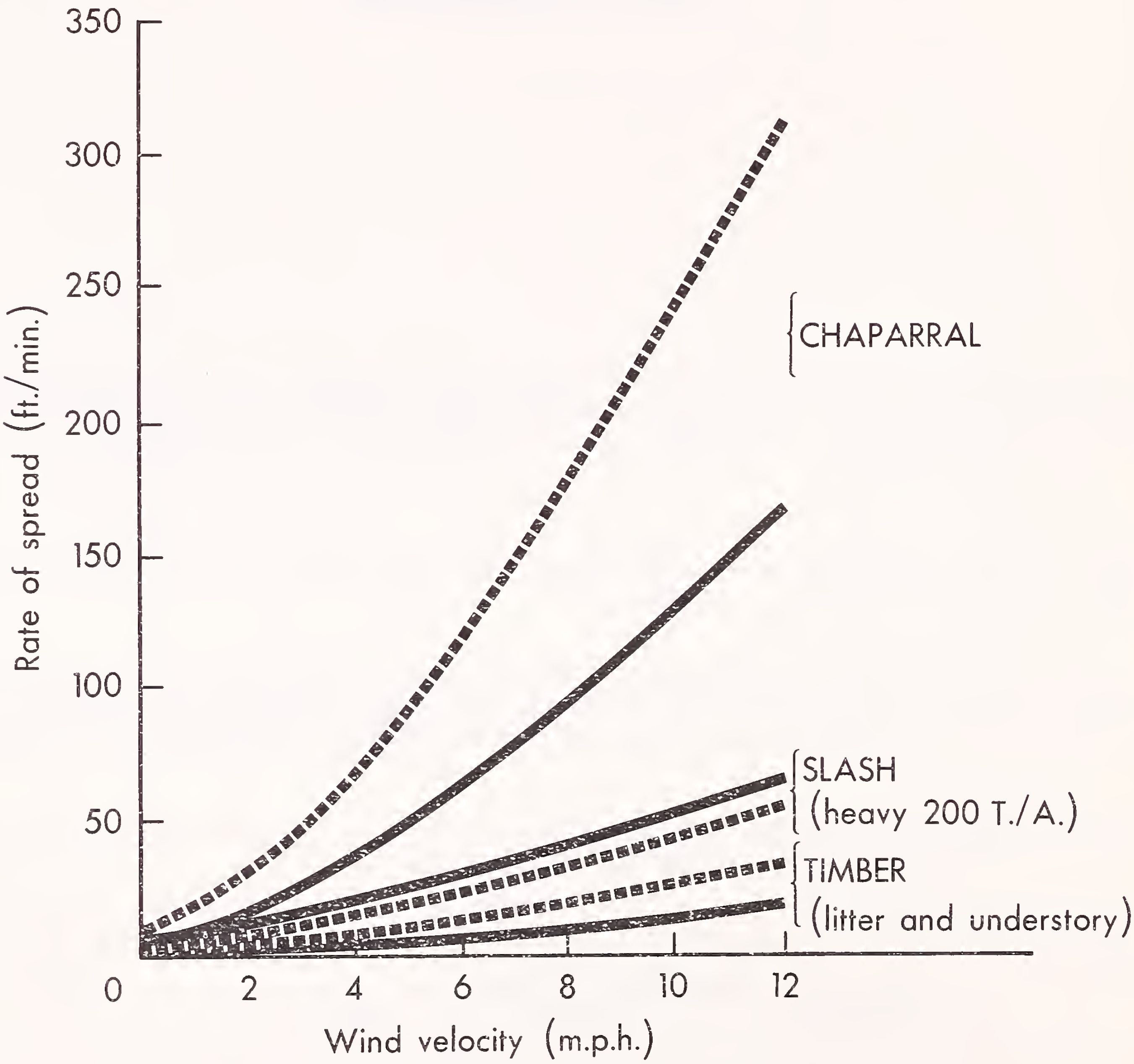

Figure 1.--Rate of fire spread versus wind velocity at midflame height for three fuel models:[1] chaparral, timber (litter and understory), and slash (heavy, 200 T/A). The solid curves represent results of the weighting parameter, the dashed curves results of the effective heating number.

Conclusions

By exchanging the weighting parameter for the effective heating number, the total reaction intensity and the rate of spread are less when the load is limited to a single category. However, the reverse is true when the load is divided into two categories. More importantly, when the effective heating number is used, the total reaction intensity and the rate of spread remain unchanged whether the load is divided into two or more categories or limited to one. Replacement of the weighting parameter, f_i, by the effective heating number, ε_i, is a reasonable alternative since it represents the fractional amount of fuel brought to ignition within the category. As used here, the effective heating number can account for the characteristic load effectively involved in the initial combustion process that creates the reaction intensity necessary to propagate the fire. It weights the category according to its characteristic fuel size and, consequently, its proportionate involvement in the spreading fire.

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